Dynamic Restoration in Multi-layer IP/MPLS-over-Flexgrid Networks

Alberto Castro, Luis Velasco, Jaume Comellas, and Gabriel Junyent
Universitat Politècnica de Catalunya (UPC), Barcelona, Spain
E-mail: acastro@ac.upc.edu

Abstract—The recent advances in photonic technology will allow deploying flexgrid-based optical core networks in the near future. Although that technology favors more efficient spectrum utilization, multilayer IP/MPLS-over-flexgrid networks would still be needed to groom together client flows, coming from access and metro networks, into optical connections. In this scenario, multi-flow transponders (MF-TP) will provide additional flexibility allowing reconfiguration of optical connections to be performed. To be operated, a distributed control plane together with a centralized Path Computation Element (PCE) could be used. In the event of a failure, tens or hundreds of client flows could become disconnected and thus, restoration routes need to be found by the PCE for these flows. In standard restoration, path computation for each client flow is performed which derives into resource contention as a result of several connections trying to use some common resources, and poor resource utilization as a result of the reduction of grooming levels. In this paper, we deal with these problems and solve the DYNamic restorAtion in Multi-layer IP/MPLS-over-flexgrid Optical networks (DYNAMO) problem. Client flows’ restoration requests are grouped into a single bulk in the PCE. Afterwards, a Global Concurrent Optimization (GCO) module solves the DYNAMO problem finding routes for all the flows in the bulk. The DYNAMO problem is modeled by using mathematical programming. However, as a consequence of its complexity and the stringent times within which the problem has to be solved, a GRASp-based heuristic is used. Exhaustive simulation results performed on two national core topologies show that a PCE with a GCO module solving DYNAMO highly improves restorability and reduces remarkably the number and capacity of MF-TPs, at the expense of some increment in restoration times.

Keywords: Flexgrid Optical Networks, Multi-layer Networks, Dynamic Bulk Restoration.

I. INTRODUCTION

Recent advances in optical modulation formats, filtering, and digital signal processing, among others, are enabling flexgrid components to be produced; finer granularity and flexibility in the use of the optical spectrum compared to that of the fixed grid can be achieved [1].

For flexgrid-based optical core networks to be deployed, bandwidth-variable optical cross-connects (BV-OXC), equipped with bandwidth-variable wavelength selective switches, and multi-flow transponders (MF-TP) need to be commercially available [2]-[4]. Installed in IP/MPLS routers and connected to a BV-OXC, MF-TPs add extra flexibility allowing several optical connections (lightpaths) to be terminated in each of them.

As a consequence of the introduction of flexgrid networks, grooming could be partially done at the optical layer reducing the amount of IP/MPLS routers that need to be installed in a network [5]. However, those routers would be still needed to fill the gap between the bitrate of IP/MPLS client flows coming from access and metro networks (e.g. 1 Gb/s) and the capacity of one slot lightpath (in the order of 10 Gb/s when 6.25 GHz slot width and the quadrature phase shift keying, QPSK, modulation format are used).

To operate those multilayer IP/MPLS-over-flexgrid networks, a distributed control plane with a centralized Path Computation Element (PCE) [6] can be used. The standardized PCE computes routes in response to path computation requests. It takes advantage of a traffic engineering database (TED) that is updated after network resources are effectively used or released.

In multilayer IP/MPLS-over-flexgrid, a failure in a single fiber link may disconnect tens or hundreds of client IP/MPLS flows. In that case, an independent restoration path computation request for each disconnected flow is received at the PCE. The standard procedure (named sequential in this paper) consists in computing a route for each request using the state of the network resources stored in the TED. However, better network-wide solutions can be achieved grouping together a set of path computation requests and performing bulk path computation. Recently, efforts to introduce enhanced computation capabilities in the PCE have concluded with the standardization of Global Concurrent Optimization (GCO) [7]. GCO aims at serving a bulk of path requests attaining the optimal solution for the whole network.

In view that the sequential approach achieves poor resource efficiency and suffers from contention problems since path computations might be performed over a non-updated TED, we propose to take advantage of bulk path computation in restoration scenarios. To this end, we define the DYNa믹 restorAtion in Multi-layer IP/MPLS-over-flexgrid Optical networks (DYNAMO) and solve it in a GCO module, which is called from a centralized PCE.

Few works addressed the application of the GCO framework. Authors in [8] present a dynamic bulk provisioning framework with the objective of optimizing the use of network resources. PCE clients are allowed to bundle
and simultaneously send multiple connection requests to the PCE where, in turn, several bundles can be concurrently processed together as a single bulk. To the best of our knowledge, however, the only work in the literature addressing bulk restoration is [9] where the authors describe an experimental implementation for bulk restoration in a GCo module called from the centralized PCE for multilayer fixed grid-based networks. Based on the lessons learned from that experimental implementation, in this paper we focus on the specific problems that arise in IP/MPLS-over-flexgrid networks.

The reminder of this paper is organized as follows. Section II describes dynamic restoration in multilayer IP/MPLS-over-flexgrid networks and presents two different approaches: sequential and bulk. The DYNAMO problem for bulk restoration is formally stated and a mathematical model to solve it is presented in Section III. Due to the fact that the model is computationally impractical when realistic problem instances are considered, a heuristic algorithm able to obtain near-optimal solutions in practical times is proposed in Section IV and used in Section V to compare the performance of the bulk restoration approach against that of the sequential one. Finally, Section VI draws the main conclusions.

II. DYNAMIC RESTORATION IN MULTILAYER NETWORKS

For illustrative purposes, Fig. 1(a) shows a simple physical network consisting of five BV-OXCs and four IP/MPLS routers. BV-OXCs are connected by bidirectional fiber links. Let us assume that one MF-TP is installed in each of the IP/MPLS routers and connected to the collocated BV-OXC. Finally, two IP/MPLS client flows are already being served. We assume that the bitrate of each flow is 1 Gb/s. Two lightpaths were established in the physical topology to support an equal number of virtual links in the virtual topology. The route of each IP/MPLS flow over the virtual topology is given in the adjacent table.

At this stage, let us assume that a new IP/MPLS demand #3 between R1 and R3 need to be served. After requesting a route to the PCE it computes R1-R2-R3, where the existing virtual link R1-R2 is reused and a new virtual link R2-R3 must be created, which triggers the new lightpath R2-R3 to be established. Refer to [10] for details on virtual links set-up. Later, another IP/MPLS demand #4 between R2 and R3 arrives and it is served through the route R2-R3, using capacity available in virtual link R2-R3. Fig. 1(b) describes the configuration of both the physical and the virtual topologies once all four IP/MPLS flows have been routed.

Next, a failure in link X1-X2 has triggered each of the affected flows (flows #1 and #3) to request a restoration route to the centralized PCE.

In Fig. 2(a) the restoration route has been computed sequentially by the PCE and signaled afterwards. Since the TED in the PCE is only updated when the resources have been effectively allocated in the network, the signaling of the restoration routes of both IP/MPLS flows have triggered two parallel lightpaths to be set-up so as to create the virtual links needed to route the IP/MPLS flows. In the example, both lightpaths could be created because enough resources, i.e. frequency slots in the links and ports in the IP/MPLS routers, were available. Frequently, nonetheless, that is not the case and resource contention may arise. In that regard, note that both restoration routes reused the virtual link R1-R4; again resource contention could arise as a consequence of not enough capacity being available for both IP/MPLS flows in that virtual link.

In Fig. 2(b) the PCE has grouped all restoration requests and performed bulk route computation. In the example, the restoration route of both IP/MPLS flows has been computed.

![Fig. 1. Example of multilayer network consisting in five BV-OXCs and four IP/MPLS routers. As a result of set-up two IP/MPLS demands a virtual topology has been created; each virtual link is supported by a lightpath in the physical topology (a). Four IP/MPLS demands have been set-up (b).](image1)

![Fig. 2. After a failure in link X1-X2, IP/MPLS demands have been restored and the virtual topology has been reconfigured. Restoration has been done sequentially (a) and bulk (b).](image2)
The bulk routing algorithm decides to create virtual link R4-R2 using that for both restoration routes, thus reducing the amount of resources used compared to the sequential approach. However, for the bulk restoration to work restoration routes need to be sequenced: one of the routes must be signaled first, so as to trigger actual virtual link creation; after waiting enough time, virtual link R4-R2 is effectively created and the second route reusing it can be signaled.

As a consequence of the efficiency that bulk restoration reaches by reusing virtual links, the number of MF-TPs ports can be reduced. Fig. 3 is intended for illustrating the above. Fig. 3(a) shows how the IP/MPLS flows have been routed before the failure; each router is equipped with a number of client ports were the IP/MPLS flows arrive. One MF-TP allowing for five lightpaths to be ended is connected to each router. For instance, in Fig. 3(a) two lightpaths are ended in the MF-TP, were flows #1 and #3 are groomed together into a single lightpath whereas flow #2 uses a different one. Flow #3 is routed through intermediate Router 2, so that flow enters in Router 2 by one of the lightpaths terminating in the MF-TP in that router and leaves it using the same MF-TP but aggregated together with flow #4 into lightpath R2-R3.

Flows. In our example, flows #1 and #3 need virtual link R4-R2 to be created. Then, one of the demands is rerouted and the other one must be delayed enough to allow the virtual link R4-R2 to be effectively created. This fact introduces a set of dependencies among the demands that must be considered so as to minimize recovery times.

To solve the bulk dynamic restoration approach, the next section first formally states the DYNAMO problem and then a mathematical programming formulation is presented.

III. THE DYNAMO PROBLEM

A. Problem Statement

The DYNAMO problem can be formally stated as follows:

**Given:**
- a network topology represented by a graph $G_o(N, L)$, being $N$ the set of BV-OXC nodes and $L$ the set of bidirectional fiber links connecting two BV-OXC nodes, excluding failed ones; each link consists of two unidirectional optical fibers.
- a set $S$ of available slots of a given spectral width for each link in $L$.
- the virtual network represented by a graph $G_v(V, E)$, being $V$ the subset of $N$ where IP/MPLS routers are placed, and $E$ the set of virtual links defining the connectivity among the IP/MPLS nodes.
- a set $D$ of IP/MPLS demands to be recovered. Each demand $d$ is defined by the tuple $\{s_d, l_d, b_d\}$, where $s_d$ and $l_d$ represent demand’s source and destination IP/MPLS routers and $b_d$ its bitrate.

**Output:**
- the routing in the virtual topology of every recovered demand,
- the routing of the new lightpaths used to serve new virtual links to be created.

**Objective:** maximize the total amount of bitrate recovered whilst minimizing the amount of resources used (i.e., slots and MF-TPs) and the total recovery time.

We have modeled the DYNAMO problem by means of a mathematical programming formulation based on pre-computing channels to ensure spectrum contiguity as described in [11]. The next subsection presents the formulation proposed.

B. Mathematical Model

The mathematical programming model for the DYNAMO problem performs routing in both the optical and the IP/MPLS layers using node-link formulations for each network layer [12]. A set of virtual links is pre-computed beforehand; each virtual link connects two locations with IP/MPLS nodes provided that a feasible optical route can be found. A set of lightpaths is available for each virtual link, although its actual route on the optical topology is determined during the resolution of the problem.
The following sets and parameters have been defined:

**Optical Topology:**

- \( N \) Set of BV-OXC nodes, index \( n \).
- \( L \) Set of fiber links, index \( l \).
- \( L(n) \) Subset of fiber links incident to BV-OXC node \( n \).
- \( \text{len}(l) \) Length of fiber link \( l \) (km).
- \( R \) Set of bitrate-reach pairs (Gb/s, km), index \( r \).
- \( \text{len}(r) \) Reach of a path using bitrate-reach pair \( r \) in km.
- \( b(r) \) Maximum bitrate of a path using bitrate-reach pair \( r \).

**Optical Spectrum:**

- \( S \) Set of frequency slots, index \( s \).
- \( C \) Set of channels, index \( c \). Each channel \( c \) contains a subset of contiguous slots.
- \( a_s^c \) Equal to 1 if slot \( s \) in fiber link \( l \) is being used.
- \( w_c^s \) Equal to 1 if channel \( c \) includes slot \( s \).
- \( b_c \) Capacity of channel \( c \) (Gb/s).

**Virtual Topology:**

- \( V \) Set of IP/MPLS routers (\( V \subseteq N \)), index \( v \) \((v = n \) provided that BV-OXC node with index \( n \) is physically connected to the IP MPLS router with index \( v \)).
- \( E \) Set of virtual links, index \( e \).
- \( P(v) \) Set of MF-TPs in IP/MPLS router \( v \), index \( p \).
- \( k(e) \) Set of routes to support virtual link \( e \), index \( k \).
- \( K(e) \) Subset of \( k(e) \) already deployed in the optical topology.
- \( K_d(e) \) Subset of \( k(e) \) not currently deployed in the optical topology.
- \( E(v) \) Subset of virtual links incident to IP/MPLS router \( v \).
- \( N(e) \) Set of end BV-OXC nodes (nodes connected to the corresponding IP/MPLS router) of virtual link \( e \).
- \( b_{ve} \) Available capacity in virtual link \( e \) using lightpath \( v \) (Gb/s).
- \( b_{pv} \) Available capacity in MF-TP \( p \) in IP/MPLS router \( v \) (Gb/s).
- \( f_{pv} \) Number of lightpaths that can be assigned to MF-TP \( p \) in IP/MPLS router \( v \).
- \( g_{epv} \) Equal to 1 if virtual link \( e \) using lightpath \( k \) ends in MF-TP \( p \) in IP/MPLS router \( v \).

**Demands to be recovered:**

- \( D \) Set of IP/MPLS demands to be recovered, index \( d \).
- \( SD(d) \) Set of \( \{s_d, t_d\} \) IP/MPLS routers of demand \( d \).
- \( b_d \) Bitrate of demand \( d \) (Gb/s).

The decision variables are:

- \( \omega_{dek} \) Binary. Equal to 1 if demand \( d \) is routed through virtual link \( e \) using lightpath \( k \), 0 otherwise.
- \( \delta_{ek} \) Binary. Equal to 1 if lightpath \( k \) of virtual link \( e \) uses channel \( c \), 0 otherwise.
- \( \lambda_{ek} \) Binary. Equal to 1 if lightpath \( k \) of virtual link \( e \) uses channel \( c \) in fiber link \( l \), 0 otherwise.
- \( \sigma_d \) Binary. Equal to 1 if demand \( d \) is recovered, 0 otherwise.
- \( \gamma_{pv} \) Binary. Equal 1 if lightpath \( k \) of virtual link \( e \) uses bitrate-reach pair \( r \).

Finally, the mathematical programming formulation for the DYNAMO problem is as follows:

maximize

\[
A_d \sum_{d \in D} b_d \cdot \sigma_d - A_d \sum_{v \in \gamma_{pv}} \sum_{p \in P(v)} \gamma_{pv} \cdot C_{\max} 
\]

subject to:

\[
\sum_{e \in E(v)} \omega_{dek} = \sigma_d \quad \forall d \in D, v \in SD(d) 
\]

\[
\sum_{e \in E(v)} \omega_{dek} \leq 2 \quad \forall d \in D, v \in SD(d) 
\]

\[
\sum_{e \in E(v)} \omega_{dek} \geq \sum_{e \in k(e)} \omega_{dek} \quad \forall d \in D, v \in SD(d), e \in E(v) 
\]

\[
b_d \cdot \omega_{dek} \leq b_{ve} \quad \forall e \in E, k \in k(e) 
\]

\[
b_d \cdot \omega_{dek} \leq \sum_{c \in C} b_{pv} \cdot \delta_{ek}^c \quad \forall e \in E, k \in k(e) 
\]

\[
\sum_{c \in C} \omega_{dek} \cdot \lambda_{ek} \cdot \gamma_{pv} \leq f_{pv} \cdot \gamma_{pv} \quad \forall v \in V, p \in P(v) 
\]

\[
\sum_{e \in E(v)} \sum_{c \in C} \omega_{dek} \cdot b_{pv} \leq g_{epv} \quad \forall v \in V, p \in P(v) 
\]

\[
\sum_{e \in E(v)} \sum_{c \in C} \omega_{dek} \cdot b_{pv} \cdot \omega_{dek} \leq b_{pv} \quad \forall v \in V, p \in P(v) 
\]

\[
\sum_{e \in E(v)} \sum_{c \in C} \omega_{dek} \cdot \omega_{dek} \cdot \delta_{ek}^c \cdot \sigma_{dek} \leq f_{pv} \cdot \gamma_{pv} \quad \forall e \in E, k \in k(e) 
\]

\[
\sum_{e \in E(v)} \sum_{c \in C} \omega_{dek} \cdot \lambda_{ek} \cdot \gamma_{pv} \leq f_{pv} \cdot \gamma_{pv} \quad \forall e \in E, k \in k(e) 
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\sum_{e \in E(v)} \sum_{c \in C} \omega_{dek} \cdot \omega_{dek} \cdot \delta_{ek}^c \cdot \sigma_{dek} \leq b_{pv} \quad \forall v \in V, p \in P(v) 
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\sum_{e \in E(v)} \sum_{c \in C} \omega_{dek} \cdot \omega_{dek} \cdot \lambda_{ek} \cdot \gamma_{pv} \leq f_{pv} \cdot \gamma_{pv} \quad \forall e \in E, k \in k(e) 
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\[
\sum_{e \in E(v)} \sum_{c \in C} \omega_{dek} \cdot \omega_{dek} \cdot \lambda_{ek} \cdot \gamma_{pv} \leq f_{pv} \cdot \gamma_{pv} \quad \forall e \in E, k \in k(e) 
\]

\[
\sum_{e \in E(v)} \sum_{c \in C} \omega_{dek} \cdot \omega_{dek} \cdot \lambda_{ek} \cdot \gamma_{pv} \leq f_{pv} \cdot \gamma_{pv} \quad \forall e \in E, k \in k(e) 
\]
\[ C_{\text{st}} = \sum_{e} (1 - \varphi_{\text{st}}) \left[ 1 - \sum_{c} \delta^{c}_{\text{st}} \right] \text{ for } e \in E, k \in K_{t}(e) \]

\[ C_{\text{max}} \leq C_{\text{st}} \text{ for } e \in E, k \in K_{t}(e) \]  

The objective function (1) maximizes the total bitrate recovered, while minimizing the use of MF-TPs and the total restoration time. Constraints (2)-(4) compute the route and perform aggregation of demands through the virtual topology. Constraints (5)-(6) allow the demands to restore for using existing virtual links or new ones, in which case new lightpaths need to be created. Constraints (7)-(12) compute the route and perform sequential restoration and, so new virtual links, to time intervals.

Note that constraint (18) entails multiplying two binary variables thus converting the mathematical model into a nonlinear one. Notwithstanding, variable multiplication can be easily solved as the expense of introducing additional binary variables and constraints. Even though, the DYNAMO problem can be considered NP-hard since simpler multilayer network problems have been proved to be NP-hard (e.g. [13]); hence its exact solving becomes impractical for the stringent times required for recovery, and, as a result, an heuristic algorithm is needed so as to provide good near optimal solutions in the time periods required for recovering.

IV. HEURISTIC ALGORITHM

In this section we propose a GRASP-based heuristic to solve the DYNAMO problem. In general, the GRASP meta-heuristic consists of two main phases: in the constructive phase, a greedy randomized construction procedure is used to build a feasible solution; in the local search phase the solution built in the first phase is improved until a local optimum is found [13].

<table>
<thead>
<tr>
<th>INPUT</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_{\text{s}} (N, L), G_{\text{v}} (V, E), D, \alpha )</td>
<td>( \text{Sol} )</td>
</tr>
</tbody>
</table>

1. \( \text{Sol} \leftarrow \emptyset; Q \leftarrow D \)
2. while \( Q \neq \emptyset \) do
3. for each \( d \in Q \) do
4. \( \text{route} = \text{shortestPath}(G_{\text{s}}, d) \)
5. if \( \text{route} = \emptyset \) then \( q(d) = -\infty \)
6. else \( q(d) \leftarrow \text{evaluate the quality} \) using eq. (23)
7. if \( q(d) > q^\text{max} \) then break
8. \( q^\text{max} \leftarrow q(d) \min \{ q(d) : \text{for each } \} \)
9. \( RCL \leftarrow \text{select an element} \) from \( RCL \) at random
10. for each \( e \in \text{route} \) do
11. \( \text{implement}(G_{\text{s}}, e) \)
12. if \( e \) is \( \text{implemented} \) then \( \text{implement}(G_{\text{v}}, d) \)
13. \( Q \leftarrow Q \setminus \{ d \} \)
14. \( \text{Sol} \leftarrow \text{Sol} \cup \{ d \} \)
15. return \( \text{Sol} \)

Table I describes the proposed greedy randomized constructive algorithm. Equation (23) is used to quantify the quality of recovering a given demand \( d \), in line with the objective function for the mathematical model. A restricted candidate list (RCL) containing those demands with the best quality is used. Parameter \( \alpha \) in the real interval \([0, 1]\) determines the size of RCL.

\[ q(d) = A_{1} \cdot \text{bw} - A_{2} \cdot d.\text{newResources} - A_{3} \cdot d.\text{depend} \]  

During the local search, the route of the demands is changed so as to try to avoid new virtual links to be created.

The heuristic was validated, for really small instances, against the mathematical formulation; in all the instances checked, the heuristic provided the optimal solution, i.e. the same solution than the one obtained from solving the mathematical model with CPLEX [14]. In light of this, the heuristic was used to obtain the results presented next.

V. ILLUSTRATIVE NUMERICAL RESULTS

The performance of the considered restoration approaches was compared on two national network topologies: the 21-node Spanish Telefónica (TEL) and the 21-node Deutsche Telekom (DT) topologies (Fig. 4) where each location contained one IP/MPLS router and one BV-OXC.

Evaluation of the restoration approaches was performed by using the simulation algorithm presented in Table II. To load the network (line 2), we developed an ad-hoc event-driven simulator in OMNET++ [15]; a dynamic network environment was simulated where incoming IP/MPLS...
connection requests arrive to the system following a Poisson process and are sequentially served without prior knowledge of future incoming connection requests. To compute the routing and spectrum allocation of the lightpaths, we used the algorithm described in [16]. The holding time of the connection requests is exponentially distributed with a mean value equal to 2 hours. Source/destination pairs are randomly chosen with equal probability (uniform distribution) among all IP/MPLS nodes. Different values of the offered network load are created by changing the inter-arrival rate while keeping the mean holding time constant. Finally, note that each point in the results is the average of $10^6/|L|$ runs and that sequential and bulk restoration approaches are executed using identical input data.

In our experiments, the bitrate of each IP/MPLS flow was set to 1 Gb/s, the QPSK modulation format was used for the optical signals, the optical spectrum width was set to 1 THz, the slot width was fixed to 6.25GHz, and each IP/MPLS router was equipped with one MF-TP, whose capacity for terminating lightpaths ranged from 2 to 5. Regarding bitrate-reach pairs, we used the values reproduced in Table III. To find the appropriate loads, we first run the simulator without cutting links and store the resulting blocking probabilities. Five traffic loads unleashing blocking probabilities ranging from 0.1% to 5% for each of the networks and MF-TP capacities considered were found.

Fig. 5 presents the percentage of un-restorability of IP/MPLS flows as a function of the amount of flows to restore for the TEL and DT networks. Five plots for both sequential and bulk restoration approaches are presented, one for each of the found traffic loads, where each point corresponds to one MF-TP capacity value. As anticipated, the sequential approach produces un-restorability values as high as 27% to above 50% as a function of the traffic load. In contrast, the bulk approach achieves un-restorability values of almost 0%, i.e. virtually all IP/MPLS flows are restored for even the most stringent traffic load. The behavior is the same for the TEL network as for the DT, as shown in Fig. 5.

Table IV gives insight on the results for the TEL network using MF-TP with capacity for 5 lightpaths. There, the amount of IP/MPLS flows to be restored ranges, on average, from 37 to 46 as a function of the load offered to the network. Un-restorability values are given for both, the sequential and the bulk approach. Two main causes behind unrestored flows are detailed: i) no route could be found during path computation; and ii) resource contention, i.e. resources where already in use during the signaling phase. The latter gets together frequency slots and existing virtual links that were

<table>
<thead>
<tr>
<th>Offered Load</th>
<th># flows to restore</th>
<th>Un-restorability Sequential</th>
<th>Un-restorability Bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Path Computation</td>
<td>Resource contention</td>
</tr>
<tr>
<td>357</td>
<td>37.14</td>
<td>47.72%</td>
<td>0.00%</td>
</tr>
<tr>
<td>378</td>
<td>39.98</td>
<td>50.10%</td>
<td>0.00%</td>
</tr>
<tr>
<td>383</td>
<td>40.71</td>
<td>49.11%</td>
<td>0.00%</td>
</tr>
<tr>
<td>395</td>
<td>43.28</td>
<td>51.95%</td>
<td>0.00%</td>
</tr>
<tr>
<td>409</td>
<td>46.59</td>
<td>53.21%</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

![Fig. 5. Unrestored IP/MPLS flows against the total amount of flows to restore for TEL (left) and DT (right) networks.](image_url)
available in the TED when the route was computed, or MF-TPs resources that are actually allocated during lightpaths’ set-up. As detailed, the reason for the high un-restorability of the sequential approach is resource contention; restoration routes are computed using the state of the resources in the TED, however, as a result of the number of path computation requests arriving at the PCE, the TED becomes immediately outdated and thus both, the same resources could be assigned to several routes, and ports availability decreases notably so no new lightpaths could be established. The bulk restoration approach, in contrast, reaches negligible un-restorability values since network resources are globally optimized. Once, restoration routes are computed for a bulk of requests, resource contention disappears completely.

Fig. 6 explores the causes of un-restorability for the sequential restoration approach when the TE L network was loaded with the intensity unleashing 1% blocking probability. As shown, when the capacity of the MF-TPs is low, the percentage of resource contention as a consequence of the lack of the resources in MF-TPs is the dominant cause of un-restorability. However, as soon as higher capacity MF-TPs are used, the main cause rapidly changes to contention in the use of existing virtual links capacity. Although not included in the paper as a result of lack of space, the same results and conclusions are valid for any other load on both TEL and DT networks.

The advantages of bulk restoration come at the cost of increasing restoration times when compared to that of the sequential approach. That is particularly noticeable for high traffic loads where large number of IP/MPLS flows need to be restored as illustrated in Fig. 7. Plots for maximum bulk restoration computation times for each network and capacity of the installed MF-TPs are presented; an almost linear trend with the amount of flows to restore can be observed.

Those computation times translate into restoration times that include both, sequencing restoration route signaling to allow new virtual links to be created prior being reused, and actual signaling. Thus, the time to restore an IP/MPLS flow depends on the depth of the dependences list for that flow and the length of the route to be signaled.

As described in the DYNAMO mathematical model above, dependence depth needs to be minimized so as to minimize restoration times in bulk restoration, and as such, it was included in the heuristic algorithm. Table V presents the dependence depth values (max, min and average) as a function of the offered load. As shown, the maximum value is

<table>
<thead>
<tr>
<th>Offered Load</th>
<th>Dependences</th>
<th>Max Computation Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 lightpaths</td>
<td>0.8</td>
<td>3.0</td>
</tr>
<tr>
<td>3 lightpaths</td>
<td>1.0</td>
<td>4.0</td>
</tr>
<tr>
<td>4 lightpaths</td>
<td>1.1</td>
<td>5.0</td>
</tr>
<tr>
<td>5 lightpaths</td>
<td>1.4</td>
<td>5.0</td>
</tr>
</tbody>
</table>
only 5, which in turn introduces a considerable delay for the last set of restoration routes to be signaled.

The histograms in Fig. 8 represent the restoration times distribution when the TEL network was loaded with the medium intensity. Cumulative distributions are also plotted. Signaling times computation were performed using equations and experimental times described in [17]. The main conclusion is that restoration times lower than 1s can be achieved even when the number of IP/MPLS flows to be restored is as high as 50; more than 50% of them being restored in less than 500ms.

VI. CONCLUSIONS

This work tackled the problem of restoration in multilayer IP/MPLS-over-flexgrid network. The standardized sequential restoration approach computes restoration paths individually for each of the restoration path requests. As a consequence, poor restorability because of low new virtual link grooming levels and really high resource contention are attained.

In view of the above and taking advantage of the recently standardized Global Concurrent Optimization (GCO) allowing for bulk path computation, the bulk restoration approach in multilayer IP/MPLS-over-flexgrid networks was proposed in this paper. To this end, the DYNamic restoration in Multi-layer IP/MPLS-over-flexgrid Optical networks (DYNAMO) problem was stated and a mathematical model was developed. However, for the stringent times needed in on-line restoration scenarios, a heuristic algorithm that provides near-optimal solutions with computation times lower than one second was proposed. The focus of that heuristic was in obtaining the highest effectiveness in terms of the objective function (maximize restorability, minimizing the amount of resources used and dependence depth). In that regard, it is worth mentioning that more efficient algorithms in terms of computation times can be devised.

The performance of both approaches was extensively assessed on two national network topologies, using an ad-hoc network simulator. The results obtained showed that the sequential restoration approach provides poor restorability even for low traffic loads. In contrast, the bulk restoration approach is able to restore almost all the disconnected IP/MPLS flows.

The main causes of the high un-restorability of the sequential approach were studied resulting in contention in the use of capacity in existing virtual links and resource availability in MF-TPs.

The increased restoration times were identified as the main disadvantage of the bulk restoration. Two main causes for those longer times were: i) longer computation times, and ii) dependence depth. The first cause can be notably improved using heuristic frameworks such as those used in [16] and computation times remarkably shorter can be achieved. However, the second cause is the really limiting factor for restoration times, since they involve long waiting times. There, several approaches can be devised such as using restoration classes to give priority to some flows.

Notwithstanding, sub-second restoration times were achieved even for high traffic loads, where as many as 50 restoration paths were computed and signaled.

REFERENCES